

AD-A128 487

STUDIES OF THE INTERACTIONS OF IONIZING RADIATIONS WITH  
COMMUNICATIONS MA..(U) OAK RIDGE NATIONAL LAB TN HEALTH  
AND SAFETY RESEARCH DIV J C ASHLEY ET AL. APR 83

1/1

UNCLASSIFIED

RADC-TR-83-87 W-7405-ENG-26

F/G 20/8

NL

START

FINISH

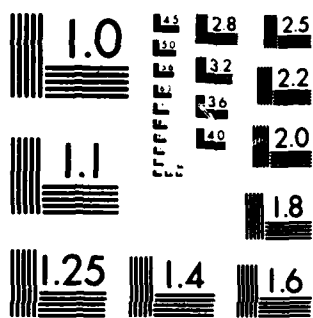
END

DATE

FILED

683

DTIC



MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A

AD A 128497

12

**RADC-TR-83-87**  
**Interim Report**  
**April 1983**



# ***STUDIES OF THE INTERACTIONS OF IONIZING RADIATIONS WITH COMMUNICATIONS MATERIALS***

**Oak Ridge National Laboratory**

**J. C. Ashley**  
**M. W. Williams**

**APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED**

**FILE COPY**

**ROME AIR DEVELOPMENT CENTER**  
**Air Force Systems Command**  
**Griffiss Air Force Base, NY 13441**

**DTIC**  
**ELECTE**

**MAY 24 1983**

**E**

**88 05 23 209**

This report has been reviewed by the RADC Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

RADC-TR-83-87 has been reviewed and is approved for publication.

APPROVED:



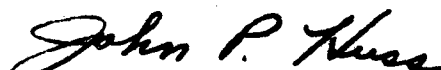
JOHN N. BRADFORD  
Project Engineer

APPROVED:



HAROLD ROTH, Director  
Solid State Sciences Division

FOR THE COMMANDER:



JOHN P. HUSS  
Acting Chief, Plans Office

If your address has changed or if you wish to be removed from the RADC mailing list, or if the addressee is no longer employed by your organization, please notify RADC (ESRE) Hanscom AFB MA 01731. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document requires that it be returned.

## UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER RADC-TR-83-87	2. GOVT ACCESSION NO. AD-A128487	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) STUDIES OF THE INTERACTIONS OF IONIZING RADIA- TIONS WITH COMMUNICATIONS MATERIALS		5. TYPE OF REPORT & PERIOD COVERED Interim Report 1 Oct 80 - 30 Sep 82
		6. PERFORMING ORG. REPORT NUMBER N/A
7. AUTHOR(s) J. C. Ashley M. W. Williams		8. CONTRACT OR GRANT NUMBER(s) RADC MIPR 81- <del>10</del> and 82-09
9. PERFORMING ORGANIZATION NAME AND ADDRESS Oak Ridge National Laboratory Helath and Safety Research Division Oak Ridge TN 37830		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2306J320
11. CONTROLLING OFFICE NAME AND ADDRESS Rome Air Development Center (ESRE) Hanscom AFB MA 01731		12. REPORT DATE April 1983
		13. NUMBER OF PAGES 32
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Same		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)  Same		
18. SUPPLEMENTARY NOTES RADC Project Engineer: John N. Bradford (ESRE)  Research sponsored jointly by the Deputy for Electronic Technology, Air Force Systems Command, under Interagency Agreement DOE No. 40-226-70 and the Office (See Reverse)		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Silicon Dioxide Mean Free Path Optical Properties of Polyethylene Track Structure In Insulators		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report summarizes experimental and theoretical studies designed to yield information on the interaction of ionizing radiations with various communica- tions materials. In studies carried out during this 2-year period, we have developed various models for calculating the energy loss per unit length, or stopping power, and the inelastic mean free path for electrons in a material. We have included both organic materials such as polyethylene and inorganic materials such as SiO <sub>2</sub> . In each case, the calculated values of stopping power and mean free path have been compared with experimental values where avail-		

DD FORM 1 JAN 73 1473

EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

able and, in the case of mean free paths for organic materials, with those predicted from our "universal" formula. In addition the various models for stopping power and mean free path have been compared with each other. Measurements have been made of electron attenuation lengths ( $\approx$  electron mean free paths) as a function of incident electron energy for electrons in amorphous carbon films, as a direct check on the values predicted by our universal formula for electron mean free paths in solid organic insulators. A theory has been developed to describe charge-particle track structure in nonmetallic solids, as the track evolves in time and space. ~~Work has~~ continued in the field of microdosimetry with the calculation of the energy densities deposited by high-energy photons as a function of depth in traversing a  $\text{SiO}_2$  slab sandwiches between two slabs of Si.

Item #18 (Con't)

of health and Environmental Research, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

# CONTENTS

PROGRAM SUMMARY . . . . .	1
I. ENERGY LOSSES AND MEAN FREE PATHS OF ELECTRONS . . . . .	3
A. Silicon Dioxide . . . . .	3
B. Summary of Mean Free Path Calculations . . . . .	4
C. Polyethylene . . . . .	4
D. Condensed Organic Materials . . . . .	4
E. Additional Model Calculations . . . . .	5
II. ELECTRON ATTENUATION LENGTHS IN CARBON . . . . .	11
III. CHARGED-PARTICLE TRACK STRUCTURE IN NON-METALLIC SOLIDS . . . .	15
IV. ELECTRON INTERACTIONS IN Si AND SiO <sub>2</sub> IRRADIATED BY PHOTONS . . . . .	16
PUBLICATIONS AND PRESENTATIONS . . . . .	21

Accession For	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A	



83 05 23 209

## PROGRAM SUMMARY

This report summarizes work done in an ongoing program under contract RAD 80007 for the periods October 1980 through September 1981 (Project Order RADC 81-10) and October 1981 through September 1982 (Project Order RADC 82-09). The objective is to gain information on the interaction of ionizing radiations with various communications materials. Thus, the intent is that work performed under this contract will increase our understanding of the basic mechanisms involved when photons, electrons, or other ionizing radiations interact with matter in its condensed phases. Emphasis is being placed on studying the interactions occurring in those materials which are currently used, or which are being considered for use, in electronics systems. Knowledge of quantities such as the cross sections for the various types of electron interactions in these materials enables predictions to be made concerning the performance of electronics systems in various situations, such as exposure to the results of a nuclear explosion. Our approach to this general problem is both theoretical and experimental. In our experimental program, we continue to make observations which can be related to photon and electron interactions with solids. The theoretical portions of the program include predictive calculations for a variety of interaction phenomena as well as interpretative studies in support of our experimental efforts. Results from the basic theoretical and experimental programs are employed in applied calculations with direct relevance to the performance of electronics systems including microsystems produced by VLSI technology.

In studies carried out during this 2-year period, we have developed various models for calculating the energy loss per unit length, or



stopping power, and the inelastic mean free path for electrons in a material. We have included both organic materials such as polyethylene and inorganic materials such as  $\text{SiO}_2$ . In each case, the calculated values of stopping power and mean free path have been compared with experimental values where available and, in the case of mean free paths for organic materials, with those predicted from our universal formula. In addition the various models for stopping power and mean free path have been compared with each other. Measurements have been made of electron attenuation lengths ( $\approx$  electron mean free paths) as a function of incident electron energy for electrons in amorphous carbon films, as a direct check on the values predicted by our universal formula for electron mean free paths in solid organic insulators. A theory has been developed to describe charged-particle track structure in nonmetallic solids, as the track evolves in time and space. Work has continued in the field of microdosimetry with the calculation of the energy densities deposited by high energy photons as a function of depth in traversing a  $\text{SiO}_2$  slab sandwiched between two slabs of Si.

The studies reported here were conducted by E. T. Arakawa, J. C. Ashley, R. N. Hamm, R. H. Ritchie, J. E. Turner, M. W. Williams, and H. A. Wright of the Health and Safety Research Division, ORNL, V. E. Anderson, Computer Sciences Division, ORNL, and T. A. Callcott, C. Martin, and L. R. Painter, Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee.

Finally, we gratefully acknowledge the continuing advice and support of J. N. Bradford of the Rome Air Development Center.

## I. ENERGY LOSSES AND MEAN FREE PATHS OF ELECTRONS

Our studies of the interaction of low-energy electrons with solids began over a decade ago and since then results from this work have been used in a wide variety of areas. It is particularly significant to note that our calculations of stopping powers of solids for electrons with energies  $\leq 10$  keV form an important part of a new report prepared for submission to the International Commission on Radiation Units and Measurements (see M. J. Berger and S. M. Seltzer, "Stopping Powers and Ranges of Electrons and Positrons," NBSIR 82-2550, August 1982). During this reporting period, these studies have continued. The results are described below.

### A. Silicon Dioxide

Earlier studies of electron interactions with  $\text{SiO}_2$  (RADC-TR-76-125, April 1976) have been re-evaluated and refined for use in the microdosimetric studies undertaken in this reporting period. New theoretical results for stopping powers and mean free paths, and comparisons with experimental data, are described in detail in the following references:

1. "Interaction of Low-Energy Electrons with Silicon Dioxide," J. C. Ashley and V. E. Anderson, *J. Electron Spectrosc. Relat. Phenom.* 24, 127-148 (1981).
2. "Energy Losses and Mean Free Paths of Electrons in Silicon Dioxide," J. C. Ashley and V. E. Anderson, *IEEE Trans. Nucl. Sci.* NS-28, 4132-4136 (1981).

B. Summary of Mean Free Path Calculations

Results for electron inelastic mean free paths in ten inorganic solids, some of which results were not readily available in the open literature, were collected and presented in a particularly simple form. Values of  $k$  and  $p$  were given for determining the mean free path  $\lambda$  as a function of electron energy  $E$  from the simple power-law expression  $\lambda = kE^p$  for values of  $E$  from 200 eV through 10 keV. The resulting table of  $k$ - $p$  values and comparisons of mean free paths with experimental data and with other theoretical results were given in the following paper: "Electron Inelastic Mean Free Paths in Several Solids for  $200 \text{ eV} \leq E \leq 10 \text{ keV}$ ," J. C. Ashley and C. J. Tung, *Surf. Interface Anal.* 4, 52-55 (1982).

C. Polyethylene

Previous results, derived using an insulator model, for the energy loss per unit path length and inelastic mean free path of an electron with an energy  $\leq 10 \text{ keV}$  [*Radiat. Res.* 83, 1-18 (1980)] were modified by including an exchange correction, a sum-rule constraint, and a small relativistic correction. These new results were compared with the previous results, with tabulated values of stopping power based on Bethe theory, and with predictions from our universal formula for organic solids in the publication "Energy Losses and Inelastic Mean Free Paths of Low-Energy Electrons in Polyethylene," J. C. Ashley, *Radiat. Res.* 90, 433-436 (1982).

D. Condensed Organic Materials

A simple, "one-mode" approximation for the wavevector- and frequency-dependent energy-loss function was employed to derive an expression for

the electron inverse mean free path,  $\lambda^{-1}$ , including the effect of exchange between the incident electron and the electrons in the medium. The inverse mean free path in a specific material can then be obtained by averaging  $\lambda^{-1}$  over the optical oscillator strength distribution which is proportional to  $\omega \text{Im}[-1/\epsilon(\omega)]$ . For materials for which the optical oscillator strength distribution may be approximated by a single, Drude-type function, especially organic materials, the general results were cast in a particularly simple form. With four constants obtained from optical data on a given material, electron mean free paths in that material can be predicted for electron energies  $\geq 150$  eV. An approximate expression was also deduced for estimating electron mean free paths in materials for which no optical data is available. Mean free paths determined from this approximate expression agree well with those obtained from our earlier universal curve predictions. For polyethylene, excellent agreement between results from this model and those of a more detailed insulator model, as described in section C, gave additional support for this simple theoretical approach. Agreement between theoretical predictions and experimental measurements of electron mean free paths in organics, which in some cases is quite good, is on the whole less than satisfactory. These results are described in detail in: "Simple Model for Electron Inelastic Mean Free Paths: Application to Condensed Organic Materials," J. C. Ashley, *J. Electron Spectrosc. Relat. Phenom.* 28, 177-194 (1982).

#### E. Additional Model Calculations

We have continued to examine simple models for the response of solids to energy and momentum transfers from low-energy electrons

( $\leq 10$  keV) for prediction of inelastic mean free paths (IMFP) and energy losses per unit pathlength. Some of these results for the IMFP were discussed in section I-D of this report. Here we discuss predictions of stopping powers. We take

$$\text{Im}[-1/\epsilon(q, \omega)] = \int_0^\infty d\omega' \omega' \text{Im}[-1/\epsilon(0, \omega')] \delta(\omega - (\omega' + q^2/2)) / \omega \quad (1)$$

for the energy-loss function which assumes a simple quadratic extension from the optical limit ( $q=0$ ) into the energy and momentum transfer plane. The energy loss per unit pathlength, in atomic units, is calculated from

$$S = \frac{2}{\pi v^2} \int d\omega \omega \int \frac{dq}{q} \text{Im}[-1/\epsilon(q, \omega)] \equiv \int d\omega \omega \tau(\frac{v^2}{2}, \omega) \quad (2)$$

where  $\omega$  and  $q$  for  $\omega \geq 0$  are restricted to values for which  $\omega \leq q(v-q/2)$ , and  $v$  is the electron speed. For a fixed  $\omega$ , the values of  $q$  lie in the range  $q_- \leq q \leq q_+$  where

$$q_{\pm} \equiv v \pm \sqrt{v^2 - 2\omega} \quad (3)$$

Equations (1)-(3) lead to

$$\tau(\frac{v^2}{2}, \omega) = \frac{1}{\pi v^2} \int_0^\infty d\omega' \omega' \text{Im}[-1/\epsilon(0, \omega')] F(\frac{v^2}{2}, \omega', \omega) \quad (4)$$

where

$$F(\frac{v^2}{2}, \omega', \omega) \equiv \theta(\omega - \frac{q_-^2}{2} - \omega') \theta(\omega' - \omega + \frac{q_+^2}{2}) / \omega(\omega - \omega') \quad (5)$$

and  $\theta(x) = 1$  for  $x > 0$  and  $\theta(x) = 0$  for  $x < 0$ . We define an exchange-corrected differential inverse mean free path  $\tau_{\text{exc}}$  by

$$\tau_{\text{exc}}\left(\frac{v^2}{2}, \omega\right) \equiv \frac{1}{\pi v^2} \int_0^\infty d\omega' \omega' \text{Im}[-1/\epsilon(0, \omega')] \left\{ F\left(\frac{v^2}{2}, \omega', \omega\right) + F\left(\frac{v^2}{2}, \omega', \frac{v^2}{2} + \omega' - \omega\right) - [F\left(\frac{v^2}{2}, \omega', \omega\right) F\left(\frac{v^2}{2}, \omega', \frac{v^2}{2} + \omega' - \omega\right)]^{1/2} \right\}, \quad (6)$$

where the expression in { } reduces to a form proportional to the non-relativistic Møller cross section when  $\omega$  and  $\frac{v^2}{2} - \omega$  are large compared to the "binding energy"  $\omega'$ . With Eq. (6),  $S$  is given by

$$S = \frac{1}{\pi v^2} \int_0^{\frac{1}{2} \frac{v^2}{2}} d\omega' \omega' \text{Im}[-1/\epsilon(0, \omega')] \int_{\omega_-}^{\frac{1}{2} \left(\frac{v^2}{2} + \omega'\right)} d\omega \omega \left\{ [\omega(\omega - \omega')]^{-1} + [(\frac{v^2}{2} + \omega' - \omega)(\frac{v^2}{2} - \omega)]^{-1} - [\omega(\omega - \omega')(\frac{v^2}{2} + \omega' - \omega)(\frac{v^2}{2} - \omega)]^{-1/2} \right\}, \quad (7)$$

$$\text{where } \omega_- \equiv \frac{1}{2} \frac{v^2}{2} \left[ 1 + \frac{2\omega'}{v^2} - \sqrt{1 - \frac{4\omega'}{v^2}} \right].$$

The integrations over  $\omega$  in Eq. (7) can be done analytically resulting in the following expression:

$$S = \frac{1}{\pi v^2} \int_0^{\frac{1}{2} \frac{v^2}{2}} d\omega' \omega' \text{Im}[-1/\epsilon(0, \omega')] \left\{ \ln \frac{1-a}{1-a-s} + \ln \frac{1+a}{1+a+s} + \frac{1}{a} \ln \left[ \frac{(1+a)(1-a+s)}{(1-a)(1+a+s)} \right] - \mathcal{F}\left(\sin^{-1} \frac{s}{1-a}, \frac{1-a}{1+a}\right) + \frac{1}{2} \ln[(1+a/2 - \sqrt{a(1+a/4)})/a] \right\}. \quad (8)$$

In this expression  $a \equiv 2\omega'/v^2$ ,  $s \equiv (1-2a)^{1/2}$ , and  $\mathcal{F}$  is an elliptic integral of the first kind defined by

$$\mathcal{F}(\phi, k) = \int_0^{\sin \phi} dx [(1-x^2)(1-k^2x^2)]^{-1/2} . \quad (9)$$

Given a set of optical data over the required energy range, the integral over  $\omega'$  in Eq. (8) could be done numerically to obtain S. However, a simple expression can be obtained by expanding the analytic functions resulting from the  $\omega$  integration in powers of  $\omega'/v^2$ . If we assume  $v^2/4$  is large compared to the value of  $\omega'$  for which  $\omega' \text{Im}[-1/\epsilon(0, \omega')]$  is largest, then only the first few terms in the expansion should be sufficient to approximate S.

Through second order terms in  $\omega'/v^2$ , we find

$$S \approx \frac{2}{\pi v^2} \int_0^{\frac{1}{2} \frac{v^2}{2}} d\omega' \omega' \text{Im}[-1/\epsilon(0, \omega')] \left[ \ln \frac{v^2}{\omega'} \sqrt{\frac{e}{8}} - \frac{3}{2} \frac{\omega'}{v^2} - \frac{1}{2} \frac{\omega'}{v^2} \ln \frac{2v^2}{\omega'} \right. \\ \left. + \sqrt{2} \left( \frac{\omega'}{v^2} \right)^{3/2} - \frac{1}{4} \left( \frac{\omega'}{v^2} \right)^2 \ln \frac{2v^2}{\omega'} - \frac{31}{12} \left( \frac{\omega'}{v^2} \right)^2 \right] . \quad (10)$$

From this form, in the large  $v$  limit, we obviously recover the non-relativistic Bethe formula

$$S_{B,NR} = \frac{\Omega_p^2}{v^2} \ln \frac{v^2}{I} \sqrt{\frac{e}{8}} , \quad (11)$$

where  $\Omega_p^2 = 4\pi n_0 Z$ ,  $n_0$  is the number of atoms or molecules per unit volume with  $Z$  electrons per atom or molecule and  $I$  is the mean excitation energy defined by

$$I = \frac{\int_0^\infty d\omega' \omega' \text{Im}[-1/\epsilon(0, \omega')] \ln \omega'}{\int_0^\infty d\omega' \omega' \text{Im}[-1/\epsilon(0, \omega')] } . \quad (12)$$

The stopping power has been evaluated from Eq. (10) for polyethylene using our optical data [*Radiat. Res.* 83, 1-18 (1980)], including carbon K-shell contributions, with the results shown in Table I ("this result").

Table I. Stopping Power of Polyethylene

E(eV)	Stopping Power in eV/Å		
	This Result	"R.R."	"Bethe"
80	2.68	3.00	2.12
100	2.92	3.14	2.67
150	2.92	3.05	2.85
200	2.72	2.82	2.73
300	2.30	2.37	2.38
400	1.97	2.05	2.08
600	1.56	1.64	1.66
800	1.31	1.38	1.40
1000	1.14	1.20	1.21
1500	0.882	0.917	0.917
2000	0.724	0.757	0.747
4000	0.437	0.454	0.445
6000	0.320	0.331	0.324
8000	0.255	0.263	0.258
10000	0.213	0.221	0.216

These results are in good agreement with our recent results, Column "R.R.," Table I, obtained using an insulator model to describe the valence electrons and generalized oscillator strengths for K-shell



ionization (see section C). Surprisingly, both sets of results agree with the Bethe-theory predictions, Eq. (11), (Column "Bethe," Table I), to within a few percent down to  $\sim 200$  eV. Part of the difference in the  $S$  values in Table I between "this result" and "R.R." is due to a difference in  $I$  in the two cases. From the energy-loss function obtained from optical data,  $I = 62$  eV. The insulator-model results ("R.R.") involved a fit of a sum of terms to  $\text{Im}[\epsilon(o, \omega)]$ . This function, plus the Kramers-Kronig relation between the real and imaginary parts of  $\epsilon$ , were used to determine the valence-electron contribution to  $\text{Im}[-1/\epsilon(o, \omega)]$ . This, plus the K-shell contribution as determined from generalized oscillator strengths, resulted in  $I = 58$  eV. This slightly smaller  $I$  corresponds to slightly larger values of  $S$  than for  $I = 62$  eV, e.g., a 7% difference in  $I$  gives about a 1.5% difference in  $S$  at 8000 eV according to Eq. (11).

The advantage of this model calculation is that a reasonably simple function, when integrated over the optical energy loss function, yields  $S$  from Eq. (10). The disadvantage is that the optical energy-loss function is not available for all materials of interest. A more general problem is that almost no measurements are available of stopping powers for electrons with energies less than 10 keV as a check on the theoretical descriptions.

## II. ELECTRON ATTENUATION LENGTHS IN CARBON

Measurements have been made of electron attenuation lengths as a function of incident electron energy over the energy range from 100 to 3000 eV for electrons in amorphous carbon films. These measurements were undertaken as a direct check on the values predicted by our universal expression for the mean free path of electrons in solid organic insulators [*Radiat. Res.* 81, 364-373 (1980); *IEEE Trans. Nucl. Sci.* NS-27, 1454-1458 (1980)].

The attenuation lengths were obtained from electron transmission measurements through self-supporting carbon films. The films were prepared by the arc evaporation of high purity carbon electrodes in vacuum. Carbon was deposited onto glass slides, which had been spin-coated with a dilute soap solution, at a rate of approximately 5 Å/sec. With the soap acting as a parting agent, the carbon films were floated off the glass slides onto distilled water, and then picked up on 829-line-per-inch Ni mesh. The films, which had thicknesses in the range from 60 to 200 Å, were examined using an optical microscope to locate continuous segments which might be suitable for the electron transmission measurements. Since electrons could be transmitted freely through holes too small to be resolved optically, only those segments for which the electron transmission became unmeasurable at low incident electron energies were used in the measurement of electron attenuation lengths.

Electrons, accelerated by an electron gun, were directed at the sample, and the electrons transmitted in a relatively large solid angle about the forward beam direction were collected. In order to discriminate against the majority of the electrons which had been scattered inelastically,

the detector incorporated a retarding potential grid which was set at ten volts less than the electron gun accelerating potential. For each incident electron energy, the electron attenuation length,  $L$ , associated with inelastic scattering was then obtained from the electron transmittance,  $T$ , using the relationship

$$T = e^{-t/L} = \frac{I - I_{BG}}{I_0 - I_{BG}},$$

where  $t$  is the sample thickness,  $I_0$  is the incident electron intensity,  $I$  is the transmitted electron intensity, and  $I_{BG}$  is the background intensity.

The experiments were performed in an ion-pumped, ultra-high vacuum chamber. To reduce the effect of magnetic fields on the electron beam, a mu-metal shield enclosed the sample region. Holes were cut in the shield for the electron gun, the detector and target assemblies, and for an observation window. Great care had to be used in the initial pump-down to avoid rupturing the fragile films. An oil-free mechanical pump, pumping through a small tube, was used first, followed by sorption and ion pumps. The ultimate vacuum was about  $10^{-8}$  Torr, increasing to  $5 \times 10^{-8}$  Torr when the electron gun was in operation.

The thicknesses of the films were determined from the measured transmittance of He-Ne laser photons, using a transmittance versus thickness curve which had been calibrated using a quartz crystal thickness monitor. The thicknesses were 76, 98, 103, and  $163 \text{ \AA}$  with experimental uncertainties in these numbers of  $\pm 20\%$ .

The electron attenuation lengths obtained for the four carbon films used in this study are shown in Fig. II-1 as a function of electron

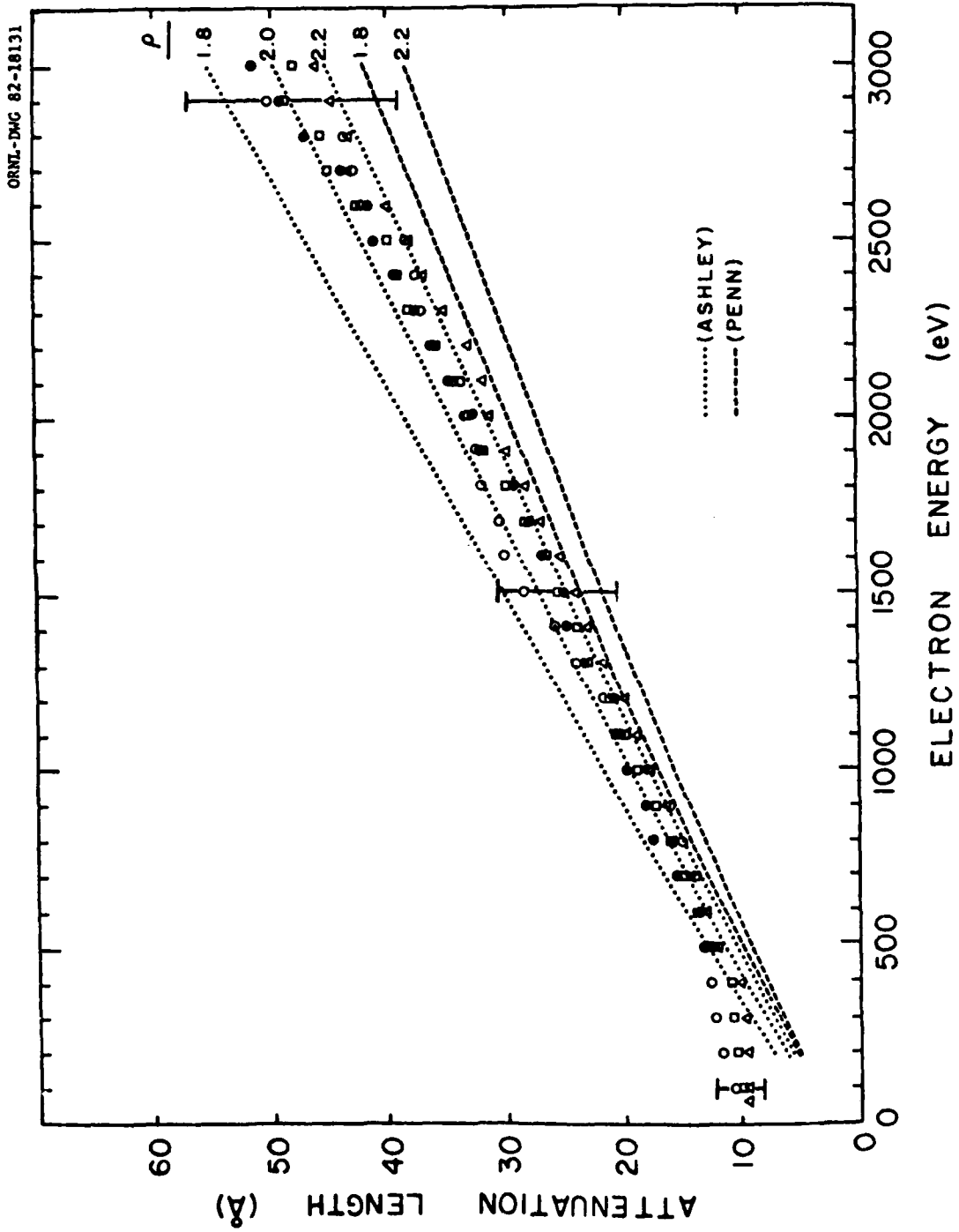


Fig. II-1

energy. Representative error bars are shown, and these result primarily from the 20% uncertainty in the film thicknesses. The dotted curves are calculated using our "universal" expression for electron mean free paths in solid organic insulators [*IEEE Trans. Nucl. Sci.* NS-27, 1454-1458 (1980)] for carbon film densities of 1.8, 2.0, and 2.2 g·cm<sup>-3</sup>. The dashed curves are calculated using Penn's equation [*J. Electron. Spectrosc. Relat. Phenom.* 9, 29-40 (1976)] based on a free electron gas model.

To make a valid comparison between experiment and theory it is necessary to know the density of the amorphous carbon films used in the electron transmission measurements. A preliminary determination of this density gave 2.1 g·cm<sup>-3</sup>. Assuming this value of density to be correct, examination of Fig. II-1 shows that the experimental values of electron attenuation length are in good agreement with the predictions of electron mean free path obtained from our universal curve from ~500 to 3000 eV. Below ~500 eV, the experimental values of electron attenuation length are larger than predicted from the universal curve. Furthermore, the observed dependence of electron attenuation length on energy is not that which is predicted. One reason for the differences between experiment and theory for incident electron energies ≤500 eV may be that some inelastically scattered electrons may be included in the measured transmitted intensity, I. Alternatively, the universal curve may not apply in this energy region. Further studies are proposed to clarify the questions raised by this study.

### III. CHARGED-PARTICLE TRACK STRUCTURE IN NON-METALLIC SOLIDS

Our core plasma model of the expanding, partially compensated positive ion track created when a densely ionizing charged particle proceeds through matter has been generalized so that the collective effects are included *a priori*. The time evolution of delta rays that are generated in the primary physical stage of the energy deposition process is followed by means of an age-type approximation that includes the self-Coulomb forces of the delta-ray distribution as well as the Coulomb attraction of the positive ion column. On a slower time scale the ion column expansion is described self-consistently in a hydrodynamical framework and the atomic recoil distribution generated in the expansion is modeled on a multi-group diffusion approximation. Calculations with this scheme will furnish a complete description of the evolution in time and space of the energy distribution of atomic recoils and the ultimate conversion of this kinetic energy into thermal energy in a detailed space-time representation. Monte Carlo checks of these calculations are planned. Some results of this work have been published in: "A Core Plasma Model of Charged Particle Track Formation in Insulators," R. H. Ritchie and C. Claussen, *Nucl. Instrum. Methods* 198, 133-138 (1982).

#### IV. ELECTRON INTERACTIONS IN Si and SiO<sub>2</sub> IRRADIATED BY PHOTONS

Preliminary calculations were carried out of the relative energy densities deposited as a function of depth by monoenergetic x-ray photons incident on a 0.5- $\mu\text{m}$  slab of SiO<sub>2</sub> sandwiched between two slabs of Si. The slabs were infinite in lateral extent and the photons entered as a parallel beam perpendicular to the planes of the Si-SiO<sub>2</sub>-Si interfaces. The front Si layer was 3- $\mu\text{m}$  thick and the back layer was essentially infinitely thick. Photon energies of 8.04 keV, 17.4 keV, and 60.0 keV were used. The first two energies are, respectively, those of the K <sub>$\alpha$</sub>  characteristic x rays of Cu and Mo. The photoelectric effect dominates in these two cases. The energy 60.0 keV was chosen as an example in which photoelectric absorption and Compton scattering are about equally probable both in the case of Si and of SiO<sub>2</sub>.

Figure IV-1 shows the energy deposited per unit volume (arbitrary units) in the array as a function of depth for irradiation by 8.04 keV photons incident from the left. The SiO<sub>2</sub> slice is located between the depths of 3.0  $\mu\text{m}$  and 3.5  $\mu\text{m}$ . Rather than selecting the photon interaction sites at random, we let them occur at uniform intervals in the Si and SiO<sub>2</sub>, the linear density being adjusted in the ratio of the total macroscopic cross sections for photon interaction. Since our primary purpose is to study the effects of the interface between the two materials, it is not necessary to have photon interactions at all depths in the array. To calculate the data for Fig. IV-1, we allowed photons to interact only between the depths of about 2.5  $\mu\text{m}$  and 4.0  $\mu\text{m}$ , indicated by the vertical arrows on the abscissa in Fig. IV-1. These depths were sufficiently far from the SiO<sub>2</sub> layer to establish electronic equilibrium in the Si on

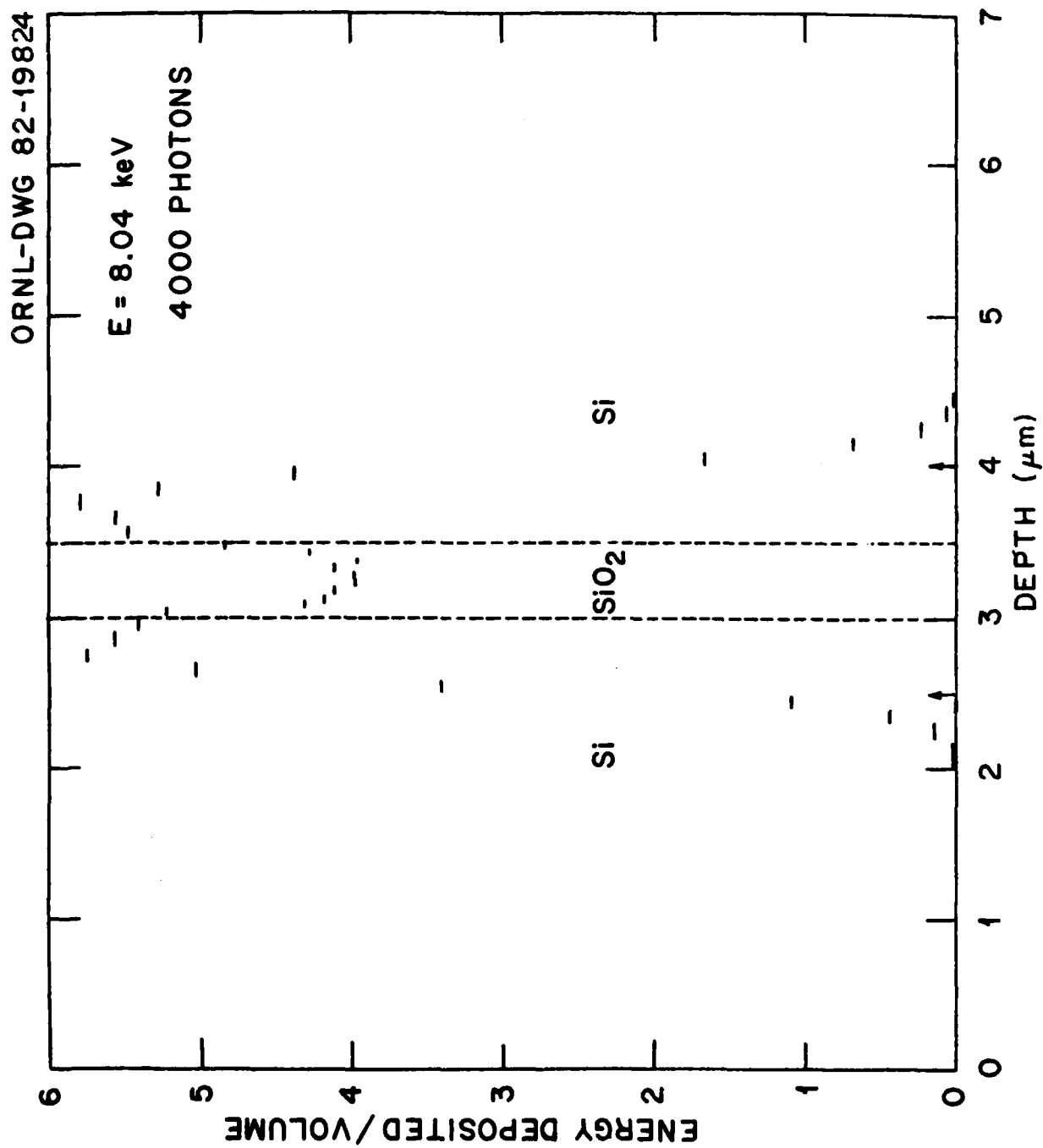


Fig. IV-1



both sides of it. The results show that the energy deposited per unit volume drops as one goes from the Si into the SiO<sub>2</sub> layer in the direction the photons are traveling. The energy deposited per unit volume then rises in going from the SiO<sub>2</sub> into the Si on the back side. These results show a gradient in energy deposition across the Si-SiO<sub>2</sub> interface. A total of 4000 photon interactions were used in obtaining the data for Fig. IV-1.

Figure IV-2 shows preliminary results for the 17.4 keV x rays. In this case 1800 photon interactions were used. An energy deposition gradient in the SiO<sub>2</sub> layer is also seen here.

Figure IV-3 shows the raw data calculated for the 60-keV photons. The statistics are poor, as only 450 interactions were used spread over the interval from 0.1 to 6.4- $\mu$ m depth. If one combines the data for the SiO<sub>2</sub> in Fig. IV-3 in intervals of 0.2  $\mu$ m instead of the 0.1  $\mu$ m shown, there is evidence of a gradient similar to those found at the two lower photon energies.

Based on these figures, final decisions will be made on the geometrical configurations and photon energies of most interest. Final computer runs will then be made with a sufficient number of photon interactions to assure satisfactory statistical resolution in the results.

ORNL-DWG 82-19825

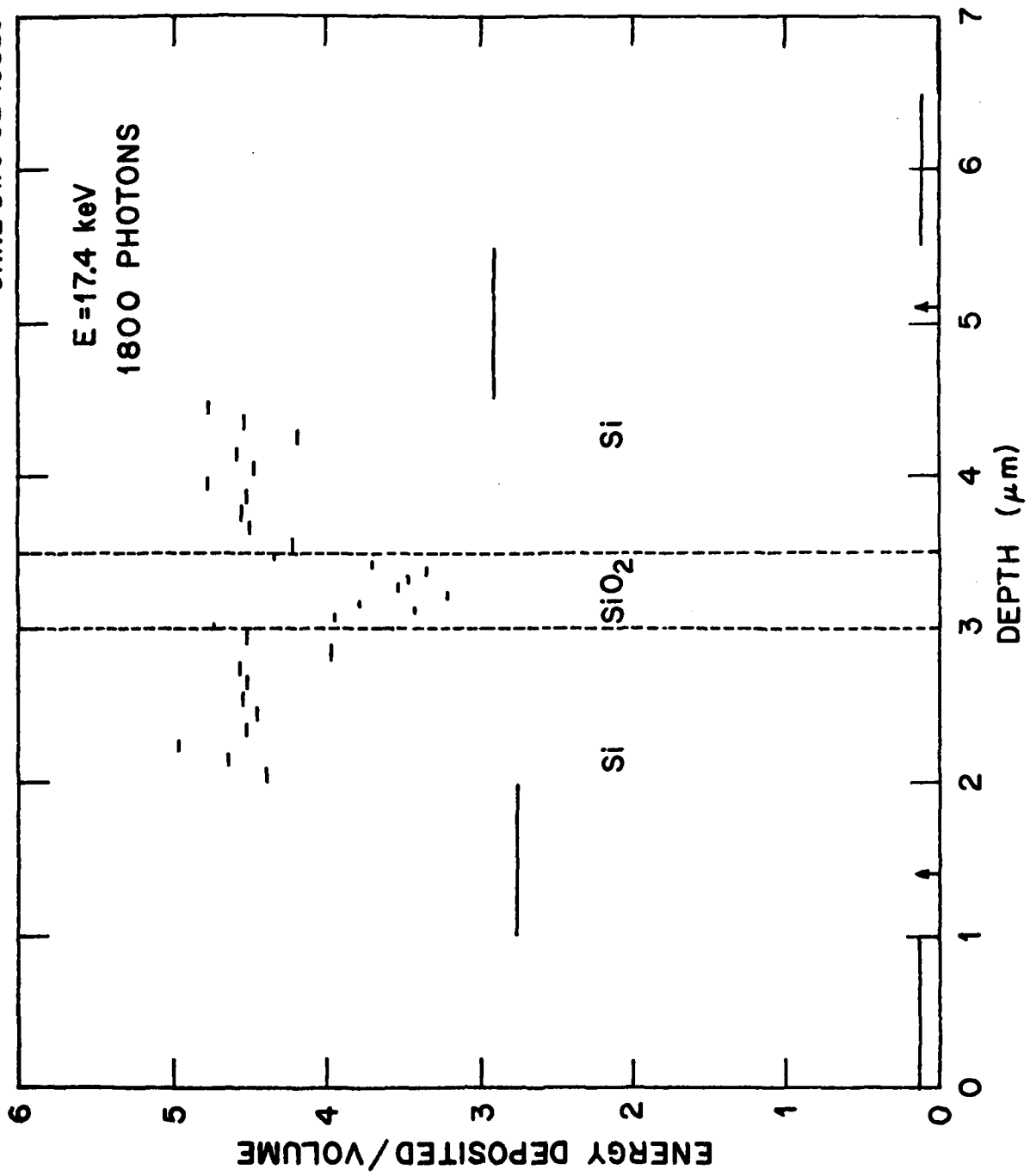


Fig. IV-2

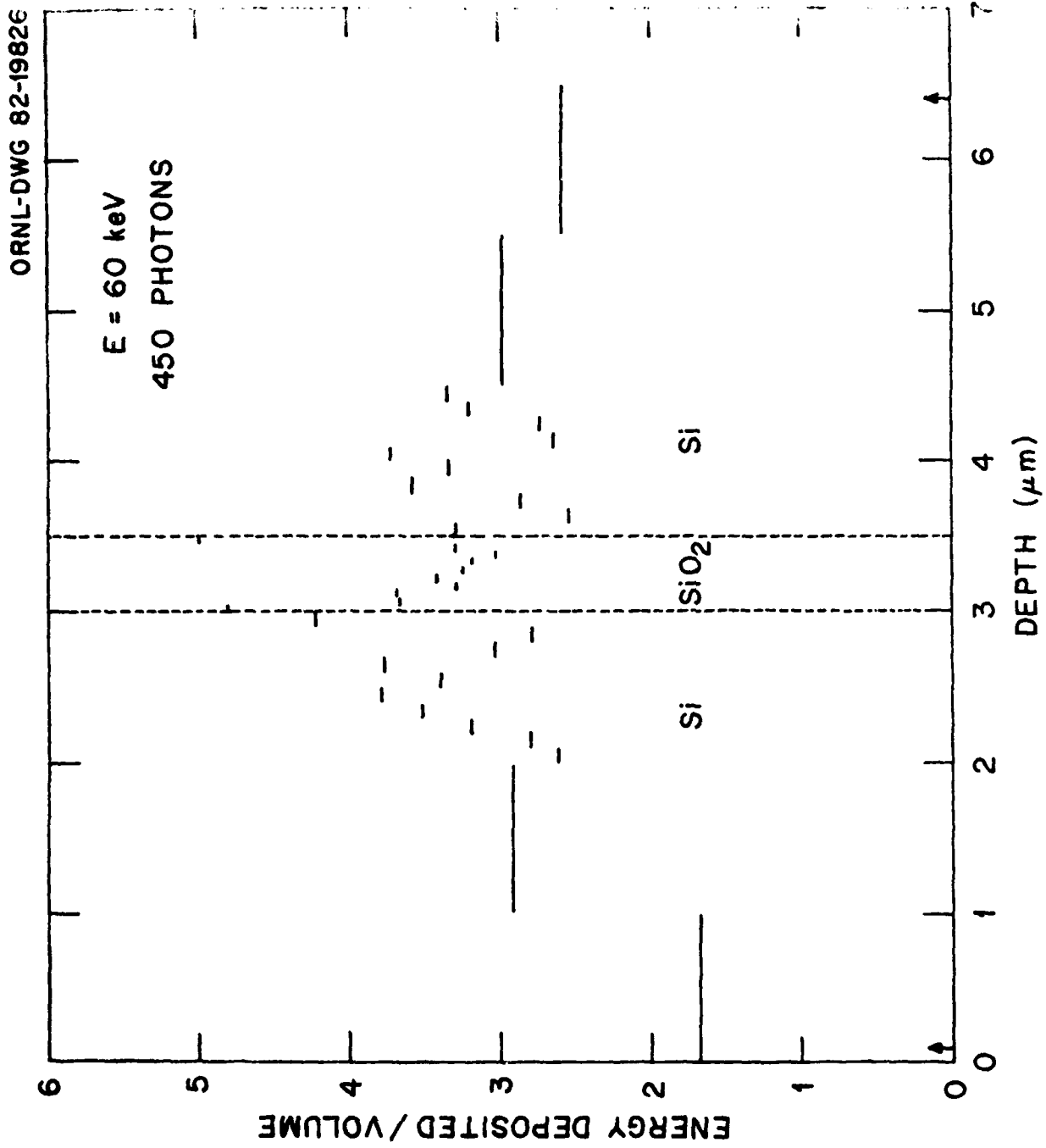


Fig. IV-3

## PUBLICATIONS AND PRESENTATIONS

During this reporting period several papers were published, or prepared for publication, and presentations were given at conferences which describe work related to this project and for which partial support by the Air Force was acknowledged. A list of these items follows.

### Publications

1. "Inelastic Interactions of Low-Energy Electrons with Organic Solids: Simple Formulae for Mean Free Paths and Stopping Powers," J. C. Ashley, *IEEE Trans. Nucl. Sci.* NS-27, 1454-1458 (1980).
2. "Studies of the Interactions of Ionizing Radiations with Communications Materials," M. W. Williams and J. C. Ashley, Air Force Final Technical Report for October 1978 through September 1980, RADC-TR-80-348 (November 1980).
3. "Calculated Distance Distributions of Energy Transfer Events in Irradiated Liquid Water," R. N. Hamm, J. E. Turner, H. A. Wright, and R. H. Ritchie, in *Proceedings of the Seventh Symposium on Microdosimetry*, edited by J. Booz, H. G. Ebert, and H. D. Hartfiel (Harwood Academic Publishers, London, 1981), pp. 717-726.
4. "Interface Effects on Dose Distributions in Irradiated Media," H. A. Wright, R. N. Hamm, and J. E. Turner, in *Proceedings of the Seventh Symposium on Microdosimetry*, edited by J. Booz, H. G. Ebert, and H. D. Hartfiel (Harwood Academic Publishers, London, 1981), pp. 293-302.
5. "The Optical Properties of Kapton: Measurement and Applications," E. T. Arakawa, M. W. Williams, J. C. Ashley, and L. R. Painter, *J. Appl. Phys.* 52, 3579-3582 (1981).

6. "Interaction of Low-Energy Electrons with Silicon Dioxide,"  
J. C. Ashley and V. E. Anderson, *J. Electron Spectrosc. Relat. Phenom.* 24, 127-148 (1981).
7. "Energy Losses and Mean Free Paths of Electrons in Silicon Dioxide,"  
J. C. Ashley and V. E. Anderson, *IEEE Trans. Nucl. Sci.* NS-28, 4132-4136 (1981).
8. "Energy Spectra of Heavy Fragments in the Interaction of Protons with Communications Materials," R. N. Hamm, M. L. Rustgi, H. A. Wright, and J. E. Turner, *IEEE Trans. Nucl. Sci.* NS-28, 4004-4006 (1981).
9. "Energy Losses and Mean Free Paths of Low-Energy Electrons in Polyethylene," J. C. Ashley, *Radiat. Res.* 90, 433-436 (1982).
10. "User's Manual for PHOEL-3, A Monte Carlo Computer Code for Calculating Initial Energies of Electrons and Positrons Produced in Water Irradiated by Photons with Energies up to 1 GeV," A. S. Todo, G. Hiromoto, J. E. Turner, R. N. Hamm, and H. A. Wright, ORNL/TM-8259 (June 1982).
11. "Electron Inelastic Mean Free Paths in Several Solids for  $200 \text{ eV} \leq E \leq 10 \text{ keV}$ ," J. C. Ashley and C. J. Tung, *Surf. Interface Anal.* 4, 52-55 (1982).
12. "Calculated Initial Energies of Electrons in Si and SiO<sub>2</sub> Irradiated by Photons with Energies Up to 2 MeV," A. S. Todo, J. E. Turner, R. N. Hamm, and H. A. Wright, *Nucl. Instrum. Methods* 203, 459-465 (1982).
13. "Monte Carlo Calculations of Initial Energies of Electrons in Water Irradiated by Photons with Energies Up to 1 GeV," A. S. Todo, G. Hiromoto, J. E. Turner, R. N. Hamm, and H. A. Wright, *Health Phys.* 43, 845-852 (1982).

14. "A Core Plasma Model of Charged Particle Track Formation in Insulators," R. H. Ritchie and C. Claussen, *Nucl. Instrum. Methods* 198, 133-138 (1982).
15. "Energy Losses by Swift Charged Particles in the Bulk and at the Surface of Condensed Matter," R. H. Ritchie, *Nucl. Instrum. Methods* 198, 81-91 (1982).
16. "Collective Aspects of Charged-Particle Track Structure in Non-Metallic Solids," R. H. Ritchie, in *Proceedings of the Eighth Symposium on Microdosimetry*, September 1982 (to be published).
17. "Simple Model for Electron Inelastic Mean Free Paths: Application to Condensed Organic Materials," J. C. Ashley, *J. Electron Spectrosc. Relat. Phenom.* 28, 177-194 (1982).
18. "Physical and Chemical Evolution of an Electron Track in Liquid Water," H. A. Wright, J. E. Turner, R. N. Hamm, R. H. Ritchie, J. L. Magee, and A. Chatterjee, in *Proceedings of the Eighth Symposium on Microdosimetry*, September 1982 (to be published).

#### Presentations

1. "Energy Spectra of Heavy Fragments in the Interaction of Protons with Communications Materials," R. N. Hamm, M. L. Rustgi, H. A. Wright, and J. E. Turner, IEEE Annual Conference on Nuclear and Space Radiation Effects, University of Washington, Seattle, Washington, July 21-24, 1981.
2. "Energy Losses and Mean Free Paths of Electrons in Silicon Dioxide," J. C. Ashley and V. E. Anderson, IEEE Annual Conference on Nuclear and Space Radiation Effects, University of Washington, Seattle, Washington, July 21-24, 1981.

3. "Physical and Chemical Evolution of an Electron Track in Liquid Water," H. A. Wright, J. E. Turner, R. N. Hamm, R. H. Ritchie, J. L. Magee, and A. Chatterjee, Eighth Symposium on Microdosimetry, Jülich, West Germany, September 27-October 1, 1982.
4. "Collective Aspects of Charged-Particle Track Structure in Non-Metallic Solids," R. H. Ritchie, Eighth Symposium on Microdosimetry, Jülich, West Germany, September 27-October 1, 1982.



## MISSION of *Rome Air Development Center*

*RADC plans and executes research, development, test and selected acquisition programs in support of Command, Control Communications and Intelligence (C<sup>3</sup>I) activities. Technical and engineering support within areas of technical competence is provided to ESD Program Offices (POs) and other ESD elements. The principal technical mission areas are communications, electromagnetic guidance and control, surveillance of ground and aerospace objects, intelligence data collection and handling, information system technology, ionospheric propagation, solid state sciences, microwave physics and electronic reliability, maintainability and compatibility.*



